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SAFE AIR-SPACE REQUIREMENTS ABOVE AN EXPLOSIVE-ORDNANCE TEST FA--ETC(U)
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MRL-R-711

SAFE AIR-SPACE REQUIREMENTS ABOVE AN EXPLOSIVE-ORDNANCE TEST FACILITY

J.D. Oliver

Approved for Public Release

FEBRUARY, 1978

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DEPARTMENT OF DEFENCE

MATERIALS RESEARCH LABORATORIES

REPORT

(14) MRL-R-711

(6) SAFE AIR-SPACE REQUIREMENTS ABOVE AN EXPLOSIVE-ORDNANCE TEST FACILITY

(10) J.D./Oliver

ABSTRACT

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(11) Feb 78 (12) 16p.

Approved for Public Release

POSTAL ADDRESS: Chief Superintendent, Materials Research Laboratories P.O. Box 50, Ascot Vale, Victoria 3032, Australia

DOCUMENT CONTROL DATA SHEET

Security classification of this page: UNCLASSIFIED

1. DOCUMENT NUMBERS:
- a. *AR Number:* AR-000-887
- b. *Series & Number:* REPORT MRL-R-711
- c. *Report Number:* MRL-R-711

2. SECURITY CLASSIFICATION:
- a. *Complete document:* UNCLASSIFIED
- b. *Title in isolation:* UNCLASSIFIED
- c. *Abstract in isolation:* UNCLASSIFIED

3. TITLE:

SAFE AIR-SPACE REQUIREMENTS ABOVE AN EXPLOSIVE-ORDNANCE TEST FACILITY

4. PERSONAL AUTHOR(S):

OLIVER, J.D.

5. DOCUMENT DATE: FEBRUARY, 1978

6. TYPE OF REPORT & PERIOD COVERED:

7. CORPORATE AUTHOR(S):

Materials Research Laboratories

8. REFERENCE NUMBERS:
- a. *Task:* ARM 94/014
- b. *Sponsoring Agency:*

9. COST CODE: (21)1330

10. IMPRINT (Publishing establishment)

Materials Research Laboratories,
P.O. Box 50, Ascot Vale, Vic.3032

FEBRUARY, 1978

11. COMPUTER PROGRAMME(S):
(Title(s) and language(s)):

12. RELEASE LIMITATIONS (of the document):

Approved for Public Release

12-0. OVERSEAS: N.O. [ ] P.R. [1] A [ ] B [ ] C [ ] D [ ] E [ ]

13. ANNOUNCEMENT LIMITATIONS (of the information on this page):

No Limitation

14. DESCRIPTORS:

Aviation Safety; Ammunition Fragments; Ballistic Trajectories; Blast Effects.

15. COSATI CODES: 0102, 1904

16. ABSTRACT (if this is security classified, the announcement of this report will be similarly classified):

Rules are presented which are believed to provide reasonably reliable guidance for the prediction of the minimum safe height for aircraft in the vicinity of an explosive-ordnance test facility.

<u>C O N T E N T S</u>

* * *

SAFE AIR-SPACE REQUIREMENTS

ABOVE AN EXPLOSIVE-ORDNANCE TEST FACILITY

1. INTRODUCTION

From time to time it becomes necessary to detonate explosive ordnance for experimental or training purposes, or in order to destroy stocks of unserviceable ammunition. Such detonations present a hazard due to blast and fragments which, insofar as it relates to personnel or structures on the ground, is fairly well understood on the basis of long experience. The hazard to aircraft in flight, however, has not been so widely studied.

Ideally this hazard should be examined by a combination of experiment and theory. But little usable information is currently available, and experiments in this area are very costly and potentially hazardous. It appears, therefore, that in the *first instance a theoretical examination* would be of some value in indicating the scale of the problem and providing tentative solutions for interim use.

This report develops and presents equations for the prediction of minimum safe height. The equations are believed to provide reasonably reliable guidance; but since they are based almost wholly on theoretical considerations they must be applied with caution. It is assumed throughout that the munitions concerned are detonated at rest on the surface of the ground.

2. HAZARD FROM FRAGMENTS

In this section we consider a munition such as an artillery shell or aircraft bomb consisting essentially of a continuous steel case enclosing an explosive charge which fills the case.

It is to be observed that some munitions in the modern armoury may differ appreciably from the conventional type described above. They may, for example, have casings of materials other than steel; or the casings may consist of pre-formed "fragments" such as steel balls (which, on vertical projection, will reach a height approximately twice that of an irregular

steel shell fragment of the same mass and initial velocity); or they may contain shaped charges which project slugs with velocities much greater than would be achieved by fragments from a conventional munition of the same charge and casing weight. Such "unconventional" munitions are excluded from consideration here since their inclusion would overload the discussion with special cases.

Single Munitions

To calculate the maximum distance to which a munition can project fragments, we need experimental data on the mass and initial velocity of all the fragments produced. From these data it is possible, on the basis of empirical rules for estimating atmospheric retardation, to compute the trajectories of the fragments and thence to deduce the fragment-hazard envelope. In particular, it is easy to calculate the maximum height to which any given fragment can ascend, and thence to deduce the minimum safe height for aircraft.

If reliable fragmentation data are unavailable this procedure cannot be followed. Nor is it applicable to a situation in which it is desired to promulgate general safety regulations for a test facility within which many different types of munition may be detonated. In such circumstances reliance must be placed on practical rules based on experience with conventional munitions; and the only such rules in general use are designed to give horizontal, not vertical, safety distances. The adaptation of such rules to the present purpose requires a knowledge of the relationship between the maximum horizontal range of a fragment and its maximum vertex height, i.e. the height to which the fragment would ascend if projected vertically. A preliminary study of fragment trajectories is therefore necessary.

As noted above, the calculation of maximum height of trajectory is readily carried out for the case of vertical projection. For other angles of departure, however, the differential equations of the motion cannot be solved in closed form to give the trajectory, and numerical methods must be applied. Consequently, in the present study, it has been found necessary to adopt the quasi-empirical approach of examining a number of numerically computed trajectories in order to determine their general character. Jenks et al. (1974) have published a compendium which gives, for selected initial conditions, the vertex height of the trajectory and the horizontal range and time of flight to graze (i.e. the point of fall on the horizontal plane through the starting point). Both spherical steel projectiles and irregular steel fragments are included; their masses (0.1 to 300 grams) and initial velocities (250 to 2500 m/s) cover the region of values likely to be encountered in practice, and results are given for angles of departure at five-degree intervals from 5° to 90°. Examination of these tables shows that the maximum horizontal range attainable by an irregular steel fragment (at an angle of departure of approximately 20° in most cases) and the maximum vertex height (for vertical projection) as defined above can be adequately related to the mass and initial velocity of the fragment by the equations:

$$R = 360\ m^{0.2849}\ v^{0.1823} \qquad (1)$$

$$H = 233\ m^{0.2782}\ v^{0.2123} \qquad (2)$$

where

R	=	maximum horizontal range	(m)
H	=	maximum vertex height	(m)
m	=	fragment mass	(kg)
v	=	initial velocity	(m/s)

For trajectories in vacuo, if gravitational acceleration is considered constant in magnitude and direction, the relationship between the maximum height H to which a projectile can rise (vertical projection) and maximum horizontal range R (projection at 45° with the same initial velocity) is

$$H/R = 0.5\ ;$$

and since the path length for R is greater than for H, the range will be more greatly reduced by air resistance than will the maximum height. Consequently, the ratio H/R will be increased by the presence of the atmosphere. The extent of this effect can be deduced from the compendium tables or from equations (1) and (2) above; for irregular steel fragments,

$$H/R = 0.647\ m^{-0.0067}\ v^{0.030}\ . \qquad (3)$$

This ratio can be seen to be insensitive to small variations in mass or velocity, and for practical purposes can be taken as having a maximum value of 0.85. Of course, by suitable choice of m and v, this value can be exceeded; but a ratio as high as 0.9, say, can only be produced by assuming unrealistic values of the parameters.

If, therefore, an acceptable absolute value of horizontal safety distance is known for a particular munition, the minimum safe height for an aircraft in respect of fragment hazard from the munition might be taken as eighty-five per cent of the horizontal safety distance, which itself is likely to incorporate a safety factor. Nevertheless, in view of the theoretical nature of the fragment trajectory calculations, it is judged wise to be conservative and equate minimum safe height with horizontal safety distance.

In the more general situation in which no official safety distance is available some general rule must be sought. One such rule is given in an ARE Report (Anon., 1953), which suggests that under peace-time conditions it would be unwise to allow unprotected personnel to be exposed to fragments from shell or medium capacity high-explosive bombs at distances smaller than those estimated from the relation

$$HDS(F) = 370\ W^{0.2}\ , \qquad (4)$$

in which HDS(F) is the horizontal danger space with respect to fragment hazard, in metres; and W is the mass of the munition (case plus charge) in kilograms. This formula, which has been converted to S.I. from the original Imperial units, appears to be suitable for the purpose. Jarret (1968) quotes it in its original form as being an approximation to a criterion introduced by the Ordnance Board in 1959, such that only one fragment per shot is expected to go beyond the formula distance. To quote Jarret: "The probability of hitting a 4-ft square target with a direct fragment at this distance is less than 10^{-6}." It thus appears safe to take VDS(F), the vertical danger space with respect to fragment hazard, as

$$\mathrm{VDS(F)} = 370\ W^{0.2} \ . \tag{5}$$

Stacked Munitions

When a number of munitions are to be detonated simultaneously in a stack, the calculation of HDS(F) and VDS(F) is affected by two main considerations.

It is conceivable that one or more of the munitions may be projected from the stack, and detonate at some later time. If this event is considered to be a possibility, the maximum range and height of the munitions' trajectories must be estimated and added to the corresponding formula distances. Good explosive practice, however, will ensure that the likelihood of such an event is negligible, and this type of event will therefore not be considered further.

The second consideration is that fragments from the outermost munition will receive additional acceleration from the blast from the innermost munitions. The magnitude of this effect cannot be precisely estimated, but an upper limit can be assigned. The gases generated by the detonation of a bare charge of high explosive leave the surface with a velocity which, for some explosives, may be as high as 4600 m/s. This velocity may be taken as the greatest velocity achievable by an explosively propelled fragment; in the present application it is likely to be a considerable over-estimate, but for hazard calculations this type of error will give an inherent safety factor.

For a munition of which the fragment masses are known, this velocity (4600 m/s) may be applied to all fragments and new danger spaces calculated by use of Equations (1) and (2); these equations have been compared with the results of specially computed trajectories with $v = 4600$ m/s and masses m from 0.1 to 3 kg and are found to predict the computed R and H with a discrepancy of not more than one per cent. As an example, consider the 105 mm shell HE M1; for this munition the greatest fragment mass observed is less than 0.06 kg and the associated velocity less than 1500 m/s. Taking these values as maxima and applying Equations (1) and (2) yields R = 613 m and H = 503 m for this fragment. (It may be noted that inserting the value of the shell mass, 15 kg, in Equation (4) yields HDS(F) = 636 m, which may be compared with the value of R just estimated.) If the fragments from a stack of 105 mm shell have velocities of 4600 m/s, the resulting maximum

ranges and heights are R = 751 m and H = 638 m, increases of 23 and 27 per cent respectively over the single-munition estimates.

For munitions of which the fragment masses are not known it is again necessary to rely on general experience. The ARE Report referred to above states :

> "It is almost impossible to make a firm estimate of the probable safety distance for a large stack of bombs as compared with that for a single unit. The ratio is almost certainly less than 2, and may very well be below 1.5. A few trials were carried out in Germany in 1946, with stacks of 231 Bombs M.C. 500 lb, in which a safety distance of 6,000 ft appeared adequate. The safety distance for a single Bomb M.C. 500 lb is usually taken as 3,600 ft."

The case given is worth examining in some detail. Equation (4) predicts a horizontal danger space of 1100 m (3600 ft) for a 500 lb (227 kg) bomb. Occasionally such a bomb might produce a fragment with a mass as high as 1 kg, and to achieve a range of 1100 m with a fragment of this mass an initial velocity of 455 m/s would be required; a height of 856 m could be reached with this velocity. The effect of increasing the velocity to 4600 m/s would give R = 1675 m or H = 1396 m, increases of 52 and 63 per cent over the single-munition estimates. One-kilogram fragments are unlikely; more realistic estimates of the parameters for the most hazardous fragments are 0.5 kg mass and 1350 m/s velocity, which yield R = 1100 m or H = 890 m. Imparting a velocity of 4600 m/s implies R = 1375 m or H = 1150 m, increases of 25 and 30 per cent. It therefore appears that the 67 per cent margin (from 3,600 ft to 6,000 ft) given in the trials described was adequate on theoretical grounds.

This and other calculations suggest that for stacked munitions an increase of 50 per cent over the formula distance for single munitions could be fairly safe, and a 75 per cent increase would be almost certainly safe, for both horizontal and vertical danger spaces. Applying the latter figure to Equation (5) yields

$$VDS(F) = 650\ W^{0.2} \tag{6}$$

for stacked munitions.

Two safety factors are implicit in this formula. The first is the assumption that VDS(F) = HDS(F) for single munitions, whereas the analysis of the previous section implies that taking VDS(F) = 0.85 HDS(F) would be reasonably safe; this gives a safety margin of 0.15/0.85, or 18 per cent. The second is the assumption that fragments may be accelerated to 4600 m/s, which is a large over-estimate; the safety margin thus provided cannot be precisely stated but is of the order of 10 per cent. Thus Equation (6) has a safety margin of about 30 per cent. Furthermore, if only two or three munitions are detonated together, it is unlikely that the danger space is appreciably greater than that for a single munition; in this situation the implied safety margin may approach 75 per cent. This aspect is examined further in connection with Example 3 of Section 4.

3. HAZARD FROM BLAST

An analysis of the hazard to which an aircraft in flight is exposed when subjected to the blast from a distant explosion is quite complex, and should properly be conducted by aeronautical experts. A heuristic examination of the problem is of some value, however, and is offered here to serve as a guide until a more detailed analysis becomes available.

From the point of view of hazard analysis, blast poses a problem which is fundamentally different from that of fragment hazard. The fragment-trajectory envelope can be calculated with fair accuracy, and an aircraft which avoids the envelope is not exposed to risk. The blast wave, by contrast, is propagated to an indefinite distance and has no finite envelope; a decision on the distance at which the risk is tolerable is therefore to some extent arbitrary.

The shock wave from an explosion can be characterised by various parameters such as peak overpressure, impulse, dynamic pressure, etc., and it is not clear which parameter is of greatest importance in the present hazard analysis. The parameter most commonly used is peak overpressure. Glasstone (1962) gives overpressures at which various degrees of damage are inflicted on parked aircraft by a nuclear burst. Light damage - "Flight of the aircraft not prevented, although performance may be restricted" - is stated to occur at overpressures of 1 psi (7 kPa) for transport aircraft and 0.5 psi (3.4 kPa) for light liaison aircraft and helicopters. It would therefore appear that blast characterised by a peak overpressure of 1 kPa would be safely tolerated, and this value is assumed in the following analysis.

The peak overpressure at a considerable distance from an explosion is difficult to estimate. Experimental data are usually obtained at comparatively short distances from the charge, and can be extrapolated to much greater distances only with caution. Stoner and Bleakeney (1948) report results from small bare charges of TNT and Pentolite detonated under "free-air" conditions (i.e. distant from reflecting surfaces) in the form

$$P = A/Z + B/Z^2 + C/Z^3 \tag{7}$$

where P = peak overpressure (atmospheres),

$Z = r/(VS)^{\frac{1}{3}}$,

r = distance from charge,) in consistent units

V = charge volume,)

S = specific gravity of the charge.

The values of the empirical constants A, B and C are such that for very large values of Z (which is in effect a dimensionless range) the expression can be approximated by

$$P = A/Z \, . \qquad (8)$$

From an examination of the constants given by Stoner and Bleakeney, the value A = 11 would appear to be adequate as a general approximation for common explosives. Taking the density of water to be 1000 kg/m^3 and one atmosphere as approximately 10^5 Pa, Equation (8) becomes :

$$p = 11 \times 10^5 \, (C_e/1000)^{\frac{1}{3}}/r \, ,$$

i.e.

$$p = 1.1 \times 10^5 \, C_e^{\frac{1}{3}}/r \, , \qquad (9)$$

where p = peak overpressure (Pa) ,

C_e = effective mass of charge (kg) .

The effective mass of the charge differs from the actual mass because of two factors :

(a) Part of the energy of the charge is used to break up the case and accelerate the fragments, and is therefore unavailable for blast production;

(b) The ground surface reflects that part of the energy which is initially directed downwards.

There are several empirical formulae (e.g. the "Fano" formulae) whereby the energy lost to fragments can be assessed. From these and other considerations it appears that for present purposes this energy loss can be ignored. The only situation in which it is important is the detonation of small charges in heavy cases, and here the main hazard is not in the blast but in the fragmentation.

If the incident energy were totally reflected by the ground, the effective charge mass C_e would be twice the actual total mass C. Kepert (1976) suggests, however, that it is rare for more than 80 per cent of the energy to be reflected, and hence it is reasonable to take

$$C_e = 1.8 \, C \, .$$

Inserting this value in Equation (9) yields

$$p = 1.4 \times 10^5 \, C^{\frac{1}{3}} /r \, . \qquad (10)$$

Then the distance r* at which the overpressure falls to the tolerable level of $p = 10^3$ Pa is given by

$$r^* = 140\ C^{\frac{1}{3}}\ , \tag{11}$$

and r* may be equated with VDS(B), the vertical danger space in respect of blast :

$$\mathrm{VDS(B)} = 140\ C^{\frac{1}{3}}\ . \tag{12}$$

Baker (1973) gives, in graphical form, a relationship between peak overpressure, range and charge energy. This relationship is based partly on experimental data and partly on theoretical considerations. At ranges of present interest Baker's graphs indicate peak overpressures somewhat smaller than those given by Equation (10); and since the graphs are not readily expressible by simple formulae it seems preferable to rely on this equation.

4. APPLICATION OF THE FORMULAE

The procedure for deciding aircraft height restrictions above gunnery ranges in Australia is laid down in "Joint Aviation Standards and Procedures" (JASAP). The calculated maximum height of the projectile trajectory above the firing point and the height of the firing point above mean sea level (AMSL) are summed, and margins are added to allow for non-standard behaviour of the projectile (the activity buffer) and for various factors affecting aircraft height-keeping (the pilot/instrument buffer). The result is rounded up to the next highest multiple of 500 ft to give the minimum height AMSL at which aircraft are permitted to fly in the vicinity of the range.

In this section it is assumed that the procedure outlined above is an acceptable basis for treating the explosive-ordnance test facility. The activity buffer is neglected, since appreciable safety factors are incorporated in the formulae; however, in particular cases it may be considered wise to add (say) ten per cent to the calculated danger spaces if the test facility is close to a busy air corridor. The pilot/instrument buffer is taken to be 500 ft (152 m).

Notation

N = number of munitions in stack

W = mass of individual munition (kg)

C = mass of explosive in each munition (kg)

Recapitulation of Formulae

(a) Fragment Hazard, single munitions :

$$VDS(F) = 370\ W^{0.2} \tag{5}$$

(b) Fragment Hazard, stacked munitions :

$$VDS(F) = 650\ W^{0.2} \tag{6}$$

(c) Blast Hazard :

$$VDS(B) = 140(NC)^{\frac{1}{3}} \tag{12a}$$

Here (NC) is the total explosive mass.

Example 1

$$N = 1 \text{ (single munition)}$$

$$W = 2000 \text{ kg}$$

$$C = 1000 \text{ kg}$$

$$\text{Eq. (5) : } VDS(F) = 370.2000^{0.2} = 1692 \text{ m}$$

$$\text{Eq. (12a) : } VDS(B) = 140.1000^{\frac{1}{3}} = 1400 \text{ m}$$

The value to be used in calculating the Vertical Danger Space (VDS) is the greater of VDS(F) and VDS(B); here the value 1692 m should be used.

Then :

Height of Firing Point AMSL (say)	:	100 m
Greater VDS (including activity buffer)	:	1692 m
Pilot/Instrument buffer	:	152 m
Sum	:	1944 m (6378 ft)

Conclusion: minimum permissible height 6500 ft AMSL.

Example 2

$$N = 10 \text{ (stacked munitions)}$$

$$W = 500 \text{ kg}$$

$$C = 250 \text{ kg}$$

$$\text{Eq. (6)} : VDS(F) = 650.500^{0.2} = 2253 \text{ m}$$

$$\text{Eq. (12a)} : VDS(B) = 140.2500^{\frac{1}{3}} = 1900 \text{ m}$$

Then:

Height of Firing Point AMSL (say)	:	225 m
Greater VDS (including activity buffer)	:	2253 m
Pilot/Instrument buffer	:	152 m
Sum	:	2630 m (8629 ft)

Conclusion: minimum permissible height 9000 ft AMSL.

Example 3

To determine the permissible detonation limits if aircraft must be allowed to operate down to a specified height.

Aircraft minimum height AMSL (say 7000 ft)	:	2134 m
Subtract: a. Height of firing point AMSL (say)	:	175 m
b. Pilot/Instrument buffer	:	152 m
Maximum allowable danger space	:	1807 m

$$\text{Eq. (12a)} : VDS(B) = 1807 = 140\ (NC)^{\frac{1}{3}},$$

$$\text{whence } NC = (1807/140)^3 = 2150 \text{ kg.}$$

Conclusion: maximum permissible explosive charge 2150 kg HE.

$$\text{Eq. (5)} : VDS(F) = 1807 = 370.W^{0.2},$$

$$\text{whence } W = (1807/370)^5 = 2778 \text{ kg.}$$

Conclusion: maximum permissible mass of a munition detonated alone is 2778 kg.

$$\text{Eq. (6)} \quad : \quad VDS(F) \; = \; 1807 \; = \; 650.W^{0.2} \, ,$$

$$\text{whence } W \; = \; (1807/650)^5 = 166 \text{ kg.}$$

Conclusion: munitions detonated in a stack must not individually have a mass greater than 166 kg.

Remarks on Example 3

This example illustrates the difficulties which will result from an uncritical application of the formula for stacked munitions. Taken literally, for instance, it would imply that two 200-kg munitions should not be fired simultaneously; yet the VDS(F) for each munition individually, calculated from Equation (5), is only 1067 m, and the effective safety margin of 740 m (i.e. 1807-1067 m) appears - and probably is - excessive.

What rule to apply for determining VSD(F) when only a few munitions are to be fired simultaneously, particularly when they are not collected in a compact stack, is at present uncertain. Perhaps the best that can be suggested is to calculate VSD(F) for the single munition and then add a margin of (say) 25 per cent. In connection with Example 3, this (suggested) rule implies an acceptable VDS(F) for the individual munition of 1807.(100/125) = 1450 m and permits firing of two or three munitions of mass $(1450/370)^5$ = 910 kg simultaneously.

5. CONCLUSION

The formulae developed and illustrated above are believed to provide reasonably reliable guidance for the prediction of the minimum safe height for aircraft in the vicinity of an explosive-ordnance test facility. Being based almost wholly on theoretical considerations, however, they must be applied with caution. In particular, they must not be allowed to over-ride existing safety regulations.

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